ATD-U-64-102

17 September 1964,

5 p.

THE INTERACTION OF COMBUSTION ZONES AND ANOMALIES IN
THE DEPENDENCE OF THE BURNING VELOCITY ON PRESSURE (Vzaimod /-
stviye stadiy Goreniya i Anomalii zavisimosti
Skoros ti Goreniya ot Davleniya).

Special Translation,

4 6 4 6 9 1

Completed
9-21-64

ATD U-64-102   17 September 1964

THE INTERACTION OF COMBUSTION ZONES AND ANOMALIES IN THE DEPENDENCE OF THE BURNING VELOCITY ON PRESSURE

Special Translation

THE INTERACTION OF COMBUSTION ZONES AND ANOMALIES
IN THE DEPENDENCE OF THE BURNING VELOCITY ON PRESSURE

The combustion of powders and condensed explosives takes place in
several successive, spatial zones; either in two zones [1,2] or in three
zones [3-5]. The anomalous increase in the temperature coefficient of
the burning velocity of powder has been explained on the basis of the
concept which considers the transition of the leading role (which con-
trols the burning velocity of the entire system) from one zone to the
other [6].

In many cases the burning velocity of a system is controlled not
by a single zone but by the interaction of several combustion zones [7].
It is possible that the constancy and also the inverse dependence of the
burning velocity on pressure, can be clarified in a number of cases by
the interaction of several combustion zones [8]. The opinion is held
that the burning velocity is independent of pressure when the leading
combustion zone is located in the condensed phase and when it is indepen-
dent of pressure [9]. From this viewpoint it is hard to find an explana-
tion for the inverse dependence of the burning velocity on pressure and
its constancy when $\nu = 0$ in a certain pressure range and at pressures
below and above this range when $\nu > 0$.

We shall schematically consider the interaction of two combustion
zones. The propagation speed of each zone (u_i) depends on the composi-
tion of the mixture, the heat and mass transfer (inside the zone and
between the zones), and, for the reaction layer of the condensed phase,
also on the relationships describing dispersion and evaporation. For a
given model we shall schematically consider that the mass burning rate
of each stage depends on the pressure p and the distance between the
zones y_i which controls the temperature and concentration gradients and
consequently also the thermal and diffusional fluxes:

$$u_1(p,\, y);\; u_2(p,\, y).$$ (1)

The second zone is located closer to the products of complete combustion
and has a higher temperature. This two-zone system must have internal
stability, i.e., after an eventual change in the distance between the
zones, the initial distance must be restored. The rate at which the
distance between the zones changes is expressed as follows:

$$\frac{dy}{dt} = \frac{1}{\rho}\,(u_1 - u_2).$$ (2)

In a steady-state regime $dy/dt = 0$ and therefore $y = y_0$, and $u_1 = u_2 = u$, where ρ is the mean density and u is the mass burning rate of the system. Let y change by a small quantity $x \cdot \exp(\mu t)$; then from equation (2) we obtain:

$$\mu = \frac{1}{\rho} \left[\left(\frac{\partial u_1}{\partial y} \right)_{y_0} - \left(\frac{\partial u_2}{\partial y} \right)_{y_0} \right]. \tag{3}$$

The system is stable when $\mu < 0$. The conditions of stability are expressed as following:

$$a_2 - a_1 > 0, \tag{4}$$

where

$$a_1 = \frac{y_0}{u} \left(\frac{du_1}{\partial y} \right)_{y_0} = \left(\frac{d \ln u_1}{d \ln y} \right)_{y_0}; \quad a_2 = \left(\frac{d \ln u_2}{d \ln y} \right)_{y_0}.$$

In order to find the dependence $y(p)$, we write the differentials of u_1 and u_2:

$$du_1 = \left(\frac{\partial u_1}{\partial p} \right)_y dp + \left(\frac{\partial u_1}{\partial y} \right)_p dy; \quad du_2 = \left(\frac{\partial u_2}{\partial p} \right)_y dp + \left(\frac{\partial u_2}{\partial y} \right)_p dy. \tag{5}$$

From equations (5) we find the relationship $y(p)$ by the use of the condition that in a steady-state regime $du_1 = du_2$:

$$\frac{dy}{dp} = \frac{p}{y} \frac{v_1 - v_2}{a_2 - a_1}; \quad \text{где } v_1 = \left(\frac{d \ln u_1}{d \ln p} \right)_y; \quad v_2 = \left(\frac{d \ln u_2}{d \ln p} \right)_y. \tag{6}$$

The values of v_1, v_2, a_1, a_2 express the over-all kinetics and also the relationships for mass and heat transfer. Inserting (6) into (5), we find:

$$v = \frac{d \ln u}{d \ln p} = \frac{a_2 v_1 - a_1 v_2}{a_2 - a_1}; \tag{7}$$

where v characterizes the dependence of the burning velocity of the system on pressure; v, v_1, v_2 may not be identical since the burning velocity of each zone depends not only on pressure but also on y.

We shall investigate under what conditions $v = 0$ or $v < 0$. The trivial case occurs when $v_1 = 0$, $a_1 = 0$ or $v_2 = 0$, $a_2 = 0$, i.e., the velocity of the controlling zone is independent of pressure.

In the general case $a_1 \neq 0$, $a_2 \neq 0$, i.e., the burning velocity depends on both zones. Then v can have values not only between v_1 and v_2 but also outside of this interval.

Let us consider the case:

$$v_1 > 0; \, v_2 > 0; \, a_1 < 0. \tag{8}$$

- 2 -

The condition $a_1 < 0$ signifies that the velocity of the first zone (u_1) increases as it approaches the second zone having a higher temperature. From formulas (4), (6), and (7) it follows that $v < 0$ in case (8), if

$$a_2 < 0; \quad v_1 > v_2; \quad dy/dp > 1. \tag{9}$$

Condition (9) signifies that at $v < 0$, for case (8), the distance between the zones increases with increasing pressure, which situation can lead to an increase in the critical combustion diameter d_{cr}; the burning velocity of the second zone decreases as the distance between the first and second zone increases. A decrease in the propagation velocity of the second zone as the latter recedes from the first zone, can take place, for instance, in the case when the reaction in the second zone takes place in the presence of short-lived active centers formed in the first zone.

It is known that the burning velocity of a number of substances does not depend on the pressure or has an inverse dependence on pressure (in a given pressure range which is characteristic for a given charge [10-12]). It is interesting that the combustion of ammonium perchlorate is attenuated in the region with $v < 0$, evidently owing to the increase of the critical diameter [10]. This agrees with the present consideration. Special studies of the limiting (critical) diameter are required because a decrease in u, also by classical considerations, leads to an increase in $d_{cr}(d_{cr} \sim 1/u$, since the characteristic dimension of the preheating zone is about $1/u$).

On the basis of the concepts developed in this article and in reference [6], the anomalous dependence between the burning velocity and and pressure can be explained as follows: At low pressures the second combustion zone is the controlling zone and $v = v_2^\circ = \partial(\ln u_2/\ln u_1)_T$; then a region follows with strong interaction of the zones and small values of $v(v < v_1; \; v < v_2)$; with further increase in pressure the first zone becomes the controlling zone and $v = v_1^\circ = (\partial \ln u_1/\partial \ln p)_T$.

The scheme described also assumes that $v \leqslant 0$ at $v_1 > 0$ and $v_2 > 0$ if $v_2 > v_1$, $a_1 > 0$, $a_2 > 0$, $dy/dp < 0$. At lower pressures the leading zone is the first zone, then a region of strong interaction follows where $v \leqslant 0$; with a further increase in pressure, the second zone becomes the controlling zone. The realization of the latter case is less probable because of the condition $a_1 > 0$.

In this paper the effect of the interaction between the zones on the dependence between the burning velocity and the pressure was considered. It is possible to study the effect of other factors on the velocity of multizone combustion with interaction of the zones. For such a study it suffices to insert in the given formulas α instead of p; where α is the parameter sought, for instance, the particle diameter, the concentration of additives, etc.

The two zones considered can be a part of a more complicated system, e.g., a three-zone system, where the two zones control the burning velocity. The burning velocity of the majority of powders, according to

present opinion, is controlled mainly by the processes taking place in the reaction layer of the condensed phase (first zone) and in the zone adjacent to the surface of the condensed phase (second zone) in which the smoke-gas or gas phase burns.

The proposed model is readily generalized for an arbitrary number of zones. For a more refined and concrete definition of the model of combustion-zone interaction, it is necessary to know the kinetics of the chemical reactions taking place in the different zones.

The objective of the study is not only a consideration of one combustion model. In this example we attempted to show that the interaction of combustion zones, in a number of cases, does not lead to a simple summation or averaging of the effect of the individual stages, but leads to qualitative new relationships, including those of the constancy and the inverse dependence of the burning rate on pressure. The concept explained can also be useful for the theory of combustion of gas mixtures.

CONCLUSIONS

In the study, a theoretical analysis was made of the interaction of combustion zones in an example of a simple model of the process. It was shown that the interaction of the combustion stages in a number of cases does not lead to a simple summation or averaging of the effect of the individual zones, but may lead to qualitatively new relationships, including those for the constancy and the inverse dependence of burning velocity on pressure. The conditions of internal stability were obtained for a model of a two-zone combustion model.

Academy of Sciences USSR   Submitted
Institute of Chemical Physics   19 November 1962

REFERENCES

1. A. F. Belyayev, Zh. fiz. khimii, 12, 93, 1938.

2. Ya. B. Zel'dovich, Zh. eksperim. 1. teor. fiz., 12, 498, 1942.

3. P. F. Pokhil, Sb. "Fizika vzryva," No. 2, 1953; No. 3, 1955; No. 5, 1956.

4. R. Parr, B. Crawford, J. Phys. Coll. Chem., 54, 929, 1950.

5. O. K. Rice, R. Ginell, J. Phys. Coll. Chem., 54, 885, 1950.

6. A. D. Margolin, Dokl. AN SSSR, 141, 1961.

7. P. F. Pokhil, Sb. "Fizika vzryva," No. 5, 1956.

8. P. F. Pokhil, O. I. Nefedova, A. D. Margolin, Dokl. AN SSSR, 145, No. 4, 1962.

9. K. K. Andreyev, A. F. Belyayev, Teoriya vzryvchatykh veshchestv, Oborongiz, 1960, 172.

10. R. Friedman, R. G. Nugent, K. E. Rumbel, A. C. Scurlock, VI
     Symposium of combustion, 1957, 612.

11. A. F. Belyayev, Ye. Kondrashkov, Dokl. AN SSSR, 131, No. 2, 1960.

12. R. F. Preckel, ARS, 31, 1286, 1961.